EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Collinear resonant ionization spectroscopy for neutron rich copper isotopes

October 7, 2011

G. Neyens[1], M. M. Rajabali[1], K. T. Flanagan[2], J. Billowes[2], M. L. Bissell[1], I. Budincevic[1], B. Cheal[2], T. E. Cocolios[3], R.F. Garcia Ruiz[1], M. Hori[4], H. A. Khozani[3,4], T. Kobayashi[5], F. Le Blanc[6], K. M. Lynch[2], 3, B. A. Marsh[3], J. Papuga[1], T. J. Procter[2], S. Rothe[3], A. Soter[4], H. H. Stoke[7], D. Verney[6], K. Wendt[8]

[1] *Instituut voor Kern- en Stralingsfysica, K.U. Leuven, Belgium*

[2] *Nuclear Physics Group, School of Physics and Astronomy, The University of Manchester, M13 9PL, United Kingdom*

[3] *ISOLDE, CERN, CH-1211, Geneva, Switzerland*

[4] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Strasse 1, D85748 Garching, Germany*

[5] *Department of Physics, School of Science, University of Tokyo, 7-3-1 Hongo Bunkyo-ku, Tokyo, Japan*

[6] *Institut de Physique Nuclaire Orsay, 15 Rue G. Clemenceau, 91406, Orsay Cedex, France*

[7] *Department of Physics, New York University, New York, NY 10003, USA.*

[8] *Institut für Physik, Mainz University, Mainz, Germany*

Spokesperson: [G. Neyens, M.M. Rajabali] [Gerda.Neyens@fys.kuleuven.be]
Contact person: [K. Flanagan] [Kieran.Flanagan@cern.ch]

Abstract: This proposal aims to study the spins, magnetic moments and quadrupole moments of copper isotopes A=76-78. The information obtained from this experiment will provide an independent and more precise measurement of the magnetic moment of ^{77}Cu and values for the spins and magnetic moments of ^{76,78}Cu as well as the quadrupole moments of $^{76-78}$Cu.

Requested shifts: [12] shifts, (split into [1] runs over [1] years)

1 Introduction

The $N = 50$ shell closure at ^{78}Ni is the most neutron rich double magic nucleus and therefore of particular interest to experimentalists and theoreticians. Nuclei in the vicinity of ^{78}Ni have only recently become available, allowing the latest theoretical developments to be validated with experimental data. Several theorists have focused their attention to this region using different approaches [1, 2, 3, 4, 5, 6, 7, 8].

The copper nuclei with one valence proton outside the $Z = 28$ closed shell provide a relatively unique opportunity to test the evolution of the shell model with neutron excess. The single proton acts as a good probe for the orbitals above the closed shell, relaying information on the rigidity of the core as well as the effect of the neutron excess on the neutron and proton orbitals. The rigidity of the $N, Z = 28$ shells have been tested by recent measurements of the magnetic moments of copper isotopes down to ^{57}Cu [9] and quadrupole moments down to ^{58}Cu [10]. Likewise, the rigidity of the $N = 50$ shell as well as the evolution of the proton single particle orbits have been tested in neutron rich nuclei by probing the ground state moments and spins. Measurements have been performed up to ^{75}Cu using collinear laser spectroscopy [11, 12], and were recently extended to ^{77}Cu using in-source laser spectroscopy [13].

The migration of the $\pi p_{3/2}$ and $\pi f_{5/2}$ states as the $\nu g_{9/2}$ orbital is filled [14, 15, 16] has motivated considerable experimental and theoretical work. Recent laser spectroscopy experiments have determined that $\pi p_{3/2}$ and $\pi f_{5/2}$ invert at $A = 75$ for copper [11] and A=79 for gallium [17]. This migration can be understood in terms of the monopole component of the tensor force which results in an attractive residual interaction between the $f_{5/2}$ odd-proton and the $g_{9/2}$ odd-neutron. As suggested in Ref [13], this attractive nature between the two orbitals may be significantly stronger than previously predicted, therefore favoring particle hole excitations across the $Z = 28$ shell gap.

A recent shell model calculation by the Strasbourg group [7] concluded that the $Z = 28$ shell gap is reduced by 0.7 MeV as the $\nu g_{9/2}$ orbital is filled. Following this, a measurement of the magnetic moment of ^{77}Cu [13] agrees with this calculation suggesting a quenching of the $Z = 28$ shell gap as the $\nu g_{9/2}$ orbital is filled. By also measuring the quadrupole moment, which is very sensitive to E2-type excitations, this proposal will provide further information on the rigidity of the $N = 50$ and $Z = 28$ shell closures.

The introduction of the ISCOOL linear Paul trap extended collinear laser spectroscopy measurements to ^{75}Cu but was unable to go further due to detection efficiency of the technique and low yields of $^{76-78}$Cu [10]. An in-source resonant ionization laser spectroscopy experiment [13] measured the spin and magnetic moment of ^{77}Cu and placed an upper limit on the magnetic moment of ^{78}Cu, but due to the Doppler broadened profile it was not possible to determine its spin nor the quadrupole moment. Using a combination of resonant ionization and collinear laser spectroscopy in the CRIS technique it is possible to greatly increase the overall experimental sensitivity while maintaining a high resolution. This will allow the model independent determination of the spins,

Table 1: The spin and magnetic moment assignments of copper isotopes of mass A=75-79. ISLS refers to In-Source Laser Spectroscopy and CLS referees to Collinear Laser Spectroscopy

Isotope	$T_{1/2}$ [ms]	Spin/Parity	μ [μ_N]	Method	Reference
^{75}Cu	1224	$5/2^-$		Beta-decay	[18]
		$5/2^-$		Beta-decay	[20]
		5/2	+1.01(5)	ISLS	[13]
		5/2	+1.0062(13)	CLS	[11]
^{76}Cu	641	3 or 4		Beta-decay	[21]
^{77}Cu	469	$5/2^-$		Beta-decay	[18]
		$5/2^-$		Beta-decay	[22]
		$5/2^-$		Shell-model	[24]
		$5/2^-$		Beta-decay	[19]
		5/2	1.61(5)	ISLS	[13]
^{78}Cu	342	6-		Beta-decay	[18]
		(4 or 5)-		Beta-decay	[21]
		At least 5		Beta-decay	[22]
		4 or 5		Beta-decay	[23]
		4- or 5-		Shell-model	[25]
		3, 4, 5 or 6	0.0(4)	ISLS	[13]
79Cu	188	$5/2^-$		Beta-decay	[18]
		5/2		Beta-decay	[23]
		$5/2^-$		Shell-model	[24]

quadrupole moments and magnetic moments of ^{76,77,78}Cu.

2 Physics motivation

The current evaluation of the spins in $^{76-78}$Cu isotopes is based mainly on decay spectroscopy studies [18, 19, 20, 21, 22, 23] with the exception of ^{77}Cu which was recently studied using in-source laser spectroscopy [13]. Table 1 summarizes the current literature values for the spin and magnetic moment assignments. ^{75}Cu and ^{79}Cu have also been added to the list to aid in the discussion below.

Decay spectroscopy studies rely on systematic trends in isotopes and beta-feeding probabilities for the Gamow-Teller and Fermi transitions to determine the spins of states populated in the daughter nuclei. To lay the foundation for level schemes built off these populated states, it is crucial to determine the spins of the ground and isomeric states of the nuclei in question. There is currently no agreement on the ground-state spins of ^{76}Cu and ^{78}Cu (Table. 1), and limited information on isomers in $^{76-78}$Cu. This work will measure the spin of ground and possible long-lived isomeric states in $^{76-78}$Cu. This

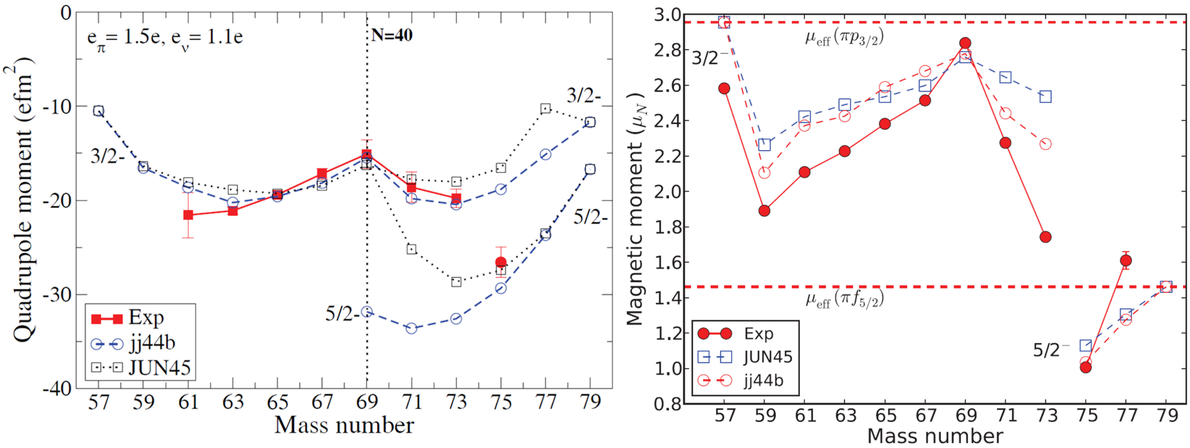

Figure 1: Experimental values are compared to theoretical predictions of quadrupole moments (left) and magnetic moments (right) for the chain of Cu isotopes. The figures are obtained from [10] and [13] for the quadrupole and magnetic moments respectively.

crucial information will help understand the structure and decay of the $^{76-78}$Ni isotopes as well as the neutron rich copper isotopes and their daughter zinc isotopes.

Magnetic moments and quadrupole moments of isotopes near shell closures are very sensitive to the leading configuration of the wave function. They can therefore aid in determining the wave function composition when compared to theoretical predictions as shown in Fig. 1. In this figure a clear distinction is observed between the moments of $3/2^-$ and $5/2^-$ states and the experimental observations agree with the theoretical predictions, which are based on a ^{56}Ni core with protons and neutrons in the $p_{3/2}f_{5/2}p_{1/2}g_{9/2}$ orbits [10, 13]. Divergence from model predictions can suggest the presence of configuration mixing. While the magnetic moments are useful for studying the particle-orbital contribution and M1-configuration mixing in the wave function ($\mathrm{f}_{7/2}$-$\mathrm{f}_{5/2}$ excitations in the case of copper), quadrupole moments provide a good measure of E2-deformation and collective behavior of the nuclei (and are thus more sensitive to $\mathrm{g}_{9/2}$-$\mathrm{d}_{5/2}$ excitations across $N = 50$).

^{78}Cu can be viewed as a ^{77}Ni core coupled to a single proton above the $Z = 28$ shell. If ^{78}Ni is considered as a doubly magic nucleus, it follows that the ^{77}Ni neutron hole in the $\nu g_{9/2}$ orbital will be an almost pure single particle state. By measuring both the magnetic moment and quadrupole moment of ^{78}Cu where the single-neutron $g_{9/2}$ hole is coupled to the single-proton $\pi f_{5/2}$ particle, it is possible to test the double magic nature of ^{78}Ni. In addition to the interest in the ground state, a possible spin gap isomer from the coupling of neutron $p_{1/2}$ and proton $f_{5/2}$ orbital may exist in ^{78}Cu. The recent work by Köster *et al.* [13] resolved only one peak in their in-source spectroscopy work, which suggests that no isomerism is present. This work could not exclude the possibility that both states have small magnetic moments and the isomer was therefore not resolved. The higher resolution afforded by the CRIS technique will clarify whether or not there is a long lived isomer in ^{78}Cu. If an isomer is observed and depending on the lifetime of the isomer, the CRIS decay spectroscopy station would provide the unique opportunity

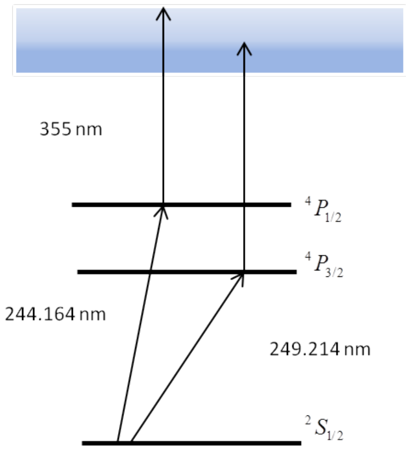

Figure 2: Ionizing scheme to be used for this experiment

to measure spectroscopic information on the decay of the isomer.

3 Experimental Method

The hyperfine structure of the neutron rich copper isotopes will be studied using collinear resonant ionization spectroscopy [26, 27] on the CRIS experimental beam line. Compared to collinear laser spectroscopy (fluorescence detection) an enhancement in sensitivity by three orders of magnitude is possible by performing resonant ionization spectroscopy (RIS) (ion detection) on a bunched beam [28]. This work will utilize the ISCOOL cooler-buncher [29] to trap the short-lived ions for up to 100ms. The bunched ion beam will be delivered to the CRIS beam line where it will be first neutralized in a charge exchange cell and then overlapped collinearly with two pulsed laser beams.

Two step RIS schemes will be used in this experiment, a resonant step from the ground state will be used to measure the hyperfine structure and laser ionization will be achieved with a second non-resonant step to the continuum. This is illustrated schematically in Figure. 2. Transitions from the ground state $3d^{10}4s\ ^2S_{1/2}$ to the $3d^94s4p\ ^4P^\circ_{1/2}$ (244.164 nm) and $3d^94s4p^4P^\circ_{3/2}$ (249.214 nm) excited states will be used for the resonant steps. The ionizating step into the continuum will use 355 nm photons. The $^4P^\circ_{1/2}$ state has been previously studied using in-gas-cell laser spectroscopy at LISOL [30, 9] and found to have a hyperfine splitting nearly 4.4 times larger than the $^2P_{1/2}$ state used in previous in-source laser spectroscopy work at ISOLDE [31, 32, 13]. The resonantly ionized copper isotopes will be subsequently delivered to the detection region, where a copper dynode and a micro channel plate detector are used for ion counting.

The CRIS beam line has now been fully constructed and all elements in the beam line have been tested using stable beams both from ISOLDE and an off-line ion source attached to the CRIS beam line. Bunching tests from ISOLDE using a variety of beams have demonstrated a bunch width between 1-2 μs in the interaction region. The charge exchange cell has been fully tested and is shown to have a neutralization efficiency of 70-90%. During charge exchange cell tests a pressure below 5×10^{-9} mbar was maintained in the interaction region. Under these conditions the background associated with collisional ionization was suppressed by a factor of 50 000. The laser laboratory has now been fully installed with two pulsed pump lasers, a pulsed dye laser, two continuous wave lasers and a pulsed dye amplifier. The ion detector has been tested and used to determine the bunch width from ISCOOL.

In the present set up we so far measured a production to detection efficiency of 3% at the end of the CRIS beam line. With such a detection efficiency yields down to 1 atom/s can be measured in cases where no large isobaric contamination is present. When a neutron converter is used the main source of isobaric contamination in this region is gallium, which has yields for ^{76}Ga of 10^5/s and 10^4/s for ^{77}Ga and ^{77}Ga. As mentioned above, the isobaric beams will be suppressed in the CRIS beam line, reducing the associated background to less than 10 ions/s. The minimum yield for ^{78}Cu that can be studied at the CRIS setup under these current conditions is 10 atoms per proton pulse.

3.1 Summary of requested shifts

We would like to request the following radioactive beams:

Table 2: Requested radioactive beams and shifts to study the spins and moments of the neutron rich ^{76,77,78}Cu ground state properties, including 3 shifts for the calibration of the transitions with respect to previous measurement.

Beam	Purpose	Expected Intensity	Target Material	Ion Source	Shifts
^{69}Cu	Reference	1.8x10^8	UCx	Laser	1
^{71}Cu	Reference	5x10^7	UCx	Laser	1
^{72}Cu	Reference	1.3x10^7	UCx	Laser	1
^{76}Cu		2.0x10^4	UCx	Laser	2
^{77}Cu		2.0x10^3	UCx	Laser	3
^{78}Cu		2.0x10^2	UCx	Laser	4
Total					**12**

Prior to the RIB run, 2 shifts with stable ^{63,65}Cu are needed to tune the experimental set up.

References

[1] P. Möller et al. *Phys. Rev. C*, 67:055802, 2003.

[2] M. Honma et al. *Phys. Rev. C*, 69(3):034335, 2004.

[3] T. Otsuka et al. *Eur. Phys. J. A*, 13(1-2):69, 2002.

[4] T. Otsuka et al. *Phys. Rev. Lett.*, 97(16):162501, 2006.

[5] J. Terasaki and J. Engel. *Phys. Rev. C*, 74:044301, 2006.

[6] M. Bender et al. *Phys. Rev. C*, 80:064302, 2009.

[7] K. Sieja and F. Nowacki. *Phys. Rev. C*, 81:061303, 2010.

[8] T. Otsuka et al. *Phys. Rev. Lett.*, 104:012501, 2010.

[9] T. E. Cocolios et al. *Phys. Rev. Lett.*, 103:102501, 2009.

[10] P. Vingerhoets et al. *Phys. Rev. C*, 82:064311, 2010.

[11] K. T. Flanagan et al. *Phys. Rev. Lett.*, 103:142501, 2009.

[12] K. T. Flanagan et al. *Phys. Rev. C*, 82:041302, 2010.

[13] U. Köster et al. *Phys. Rev. C*, 84:034320, 2011.

[14] S. Franchoo et al. *Phys. Rev. Lett.*, 81(15):3100–3103, 1998.

[15] S. Franchoo et al. *Phys. Rev. C*, 64:054308, 2001.

[16] T. Otsuka et al. *Phys. Rev. Lett.*, 95(23):232502, 2005.

[17] B. Cheal et al. *Phys. Rev. Lett.*, 104:252502, 2010.

[18] C. J. Gross et al. *Acta Phys. Pol. B*, 40:447, 2009.

[19] S. V. Ilyushkin, , et al. *Phys. Rev. C*, 80:054304, 2009.

[20] S. V. Ilyushkin, , et al. *Phys. Rev. C*, 83:014322, 2011.

[21] J. Van Roosbroeck et al. *Phys. Rev. C*, 71:054307, 2005.

[22] N. Patronis et al. *Phys. Rev. C*, 80:034307, 2009.

[23] J.A. Winger et al. *Acta Phys. Pol. B*, 39(2):525, 2008.

[24] A. F. Lisetskiy et al. In *The 4th International Conference on Exotic Nuclei and Atomic Masses*, pages 95–96. 2005.

[25] N. A. Smirnova et al. *Phys. Rev. C*, 69:044306, 2004.

[26] K. T. Flanagan et al. Collinear resonant ionization laser spectroscopy of rare francium isotopes. INTC proposal, Feb 2008.

[27] B. Cheal and K. T. Flanagan. *J. of Phys. G*, 37(11):113101, 2010.

[28] K. T. Flanagan. PhD thesis, The University of Manchester, 2004.

[29] E. Mane et al. *Eur. Phys, J. A*, 42:503, 2009.

[30] T. E. Cocolios et al. *Phys. Rev. C*, 81:014314, 2010.

[31] L. Weissman et al. *Phys. Rev. C*, 65:024315, 2002.

[32] N. J. Stone et al. *Phys. Rev. C*, 77:067302, 2008.

Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: CRIS beamline with no additions and the use of ISCOOL

Part of the	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: CRIS)	☒ Existing	☒ To be used without any modification
[Part 1 of experiment/ equipment]	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed CRIS installation.
Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): 3kW